

# Recent multi-wavelength campaigns in the *Fermi*-GST era

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**Abstract.** Since 2008 the *Fermi*/LAT instrument has delivered highly time-resolved  $\gamma$ -ray spectra and detailed variability curves for a steadily increasing number of AGN. For detailed AGN studies the *Fermi*/LAT data have to be combined with, and accompanied by, dedicated ground- and space-based multi-frequency observations. In this framework, the *Fermi* AGN team has realized a detailed plan for multi-wavelength campaigns including a large suite of cm/mm/sub-mm band instruments. Many of those campaigns have been triggered, often for sources detected in flaring states. We review here a few interesting results recently obtained during three such campaigns, namely for the flat-spectrum radio quasar 3C 279, the Narrow Line Seyfert 1 PMN J0948+0022 and quasar 3C 454.3.

## 1. Introduction

The successful launch in 2008 and subsequent smooth operation of the *Fermi* Gamma-ray Space Telescope (*Fermi*-GST) has brought the community a powerful instrument which is monitoring the entire  $\gamma$ -ray sky about every 3 hours. Thus, as an “all-sky-monitor”, *Fermi*/LAT delivers highly time-resolved  $\gamma$ -ray spectra and detailed variability curves for a steadily increasing number of AGN. For the first time, detailed studies of AGN properties at  $\gamma$ -ray energies become possible and already many interesting results have been obtained (e.g., Abdo et al. 2009c, Abdo et al. 2010a, Abdo et al. 2010c). However, only when combined with, and accompanied by, dedicated ground- and space-based multi-frequency observations, can the *Fermi*/LAT unfold its full capability of providing a tremendous opportunity for systematic and detailed studies of the physical processes at work in AGN. Consequently, a large suite of different multi-wavelength (MW) monitoring data and projects (“single-dish”, VLBI, polarization, spectra) across the whole electromagnetic spectrum (cm/mm/sub-mm, IR/optical/UV, X-ray, TeV) are essential to complement the *Fermi*  $\gamma$ -ray observations. Together, important fundamental questions about e.g.,  $\gamma$ -ray production, overall emission and variability processes as well as the location of the  $\gamma$ -ray emission region can be effectively addressed.

In this framework, the *Fermi* AGN group has realized a detailed plan for ad-hoc as well as intensive long-term campaigns. Many of these have been triggered, often for sources detected in flaring states. Here, the 15 GHz OVRO 40-m and F-GAMMA cm to sub-mm (Effelsberg 100-m, IRAM 30-m, APEX 12-m) monitoring programs, the GASP (radio/IR/optical) collaboration

including many IR/optical telescopes (radio: UMRAO, Metsähovi, SMA, Medicina, Noto), RATAN-600, ATCA, Kanata, ATOM, SMARTS, Stewart observatory, MDM, WIRO, KVA, INAOEP, VLT/VISIR as well as VLBI: MOJAVE, TANAMI, the Boston 43 GHz program, a VLBA multi-frequency ToO program and the EVN/LBA have been participating in one or more of the various campaigns.

In addition the X-ray bands have often been covered by the space-based X-ray observatories *Swift*, *Suzaku*, and RXTE. In particular, *Swift* has proven to be extremely valuable in quickly providing detailed and simultaneous observations at optical/UV and X-ray bands for many sources. Furthermore, *Spitzer* has participated in the case of 3C 454.3 with important near-IR data. Finally, first combined *Fermi*/LAT and TeV campaigns led to joint studies with the Cherenkov telescopes HESS and VERITAS as e.g., in the case of PKS 2155-304 (Aharonian et al. 2009) and 3C 66A (Abdo et al. in prep.).

Since the launch of *Fermi*-GST in 2008, many sources have been target of detailed MW campaigns triggered by the *Fermi* AGN group. Table 1 provides a short summary of those which have been published so far. Many other MW campaign publications are accepted, have been submitted or are in progress, e.g., for the galactic plane source J 0109+6134 (Abdo et al. 2010d), PKS 1510-089, Mrk 501, Mrk 421 and 3C 454.3.

As examples, we review here a few interesting results from three selected MW campaigns recently conducted (2008–2009) by the *Fermi* AGN group together with many MW collaborators.

## 2. The $\gamma$ -ray/optical polarization angle event in 3C 279

After about 100 days of *Fermi*/LAT routine operations, the quiescent phase of flat-spectrum radio quasar (FSRQ) 3C 279 turned into a phase of strong  $\gamma$ -ray activity and a MW campaign was triggered including a large number of instruments (see Fig. 1, Abdo et al. 2010b).

\* The work reviewed here was possible only due to the large efforts and great work of many multi-wavelength (MW) projects/collaborators, it is impossible to mention all in detail here. Representatively, we give the names of the corresponding projects in the text. The collaborators are part of the referenced publications for each campaign.

**Table 1.** Publication summary of sources studied by the *Fermi* AGN group including (quasi-) simultaneous MW data. Joint GeV/TeV projects are also included.

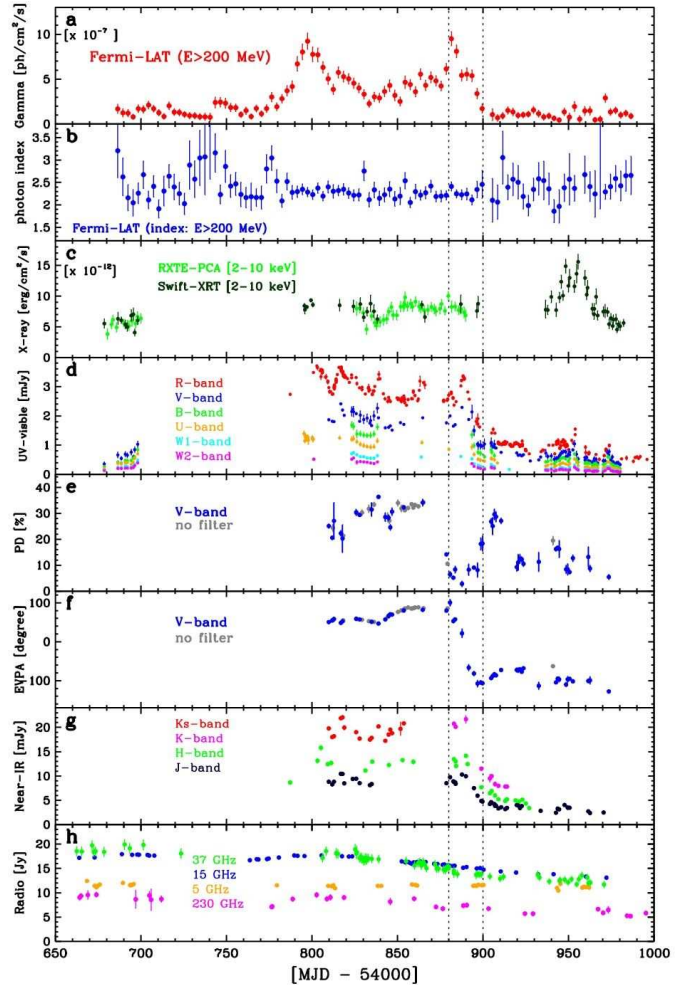
Source	Reference
RGB J0710+591	Acciari, V. A., et al. 2010, ApJ, 715, L49
5 FSRQs	Abdo, A. A., et al. 2010, ApJ, 716, 835
PKS 1424+240	Acciari, V. A., et al. 2010, ApJ, 708, L100
3C 279	Abdo, A. A., et al. 2010, Nature, 463, 919
PKS 1502+106	Abdo, A. A., et al. 2010, ApJ, 710, 810
NGC 1275	Acciari, V. A., et al. 2009, ApJ, 706, L275, Abdo, A. A., et al. 2009, ApJ, 699, 31
3C 454.3	Abdo, A. A., et al. 2009, ApJ, 699, 817
PKS 2155-304	Aharonian, F., et al. 2009, ApJ, 696, L150
PMN J0948+0022	Abdo, A. A., et al. 2009, ApJ, 707, 727, Abdo, A. A., et al. 2009, ApJ, 699, 976
PKS 1454-354	Abdo, A. A., et al. 2009, ApJ, 697, 934

As seen from Fig. 1, 3C 279 went into a high  $\gamma$ -ray state at around MJD 54780 lasting for about 120 days and characterized by a double-peak structure with overall variations of the flux by a factor  $\sim 10$ . The observed  $\gamma$ -ray luminosity of  $\sim 10^{48}$  erg s $^{-1}$  dominates the power emitted across the whole electromagnetic spectrum (see Fig. 2).

The most striking event occurred during the rapid, second  $\gamma$ -ray flare (around MJD 54880, doubling time scale of about one day). Here, a highly correlated behavior of the  $\gamma$ -ray and optical bands is evident between MJD 54800 and 54830, with the  $\gamma$ -ray flare coincident with a significant drop of the level of optical polarization, from about 30 % down to a few percent lasting for about 20 days. In particular, this event is associated with a dramatic change of the electric vector position angle (EVPA) by  $208^\circ$  ( $12^\circ$ /day), in contrast to being relatively constant earlier, at about  $50^\circ$ , which corresponds to the jet direction of 3C 279 as observed by VLBI. The close association of the  $\gamma$ -ray flare with the optical polarization angle event clearly suggests that the  $\gamma$ -ray emission was produced in a single, coherent event and happened co-spatial with the optical. It furthermore suggests highly ordered magnetic fields in the  $\gamma$ -ray emission region.

Compared to the higher energy emission, the radio cm/mm bands showed less strong variability and no obvious “correlated event” is evident from the light curves shown in Fig. 1. Still, the source appears to be at higher radio flux levels (factor  $\sim 2$ ) during the period of the overall  $\gamma$ -ray high state as seen from the 230 GHz SMA data. However, assuming the source was still optically thick at these bands, synchrotron self-absorption arguments constrain the transverse size of the emission region to  $< 5 \times 10^{16}$  cm, in good agreement with the values obtained from the shortest  $\gamma$ -ray variability.

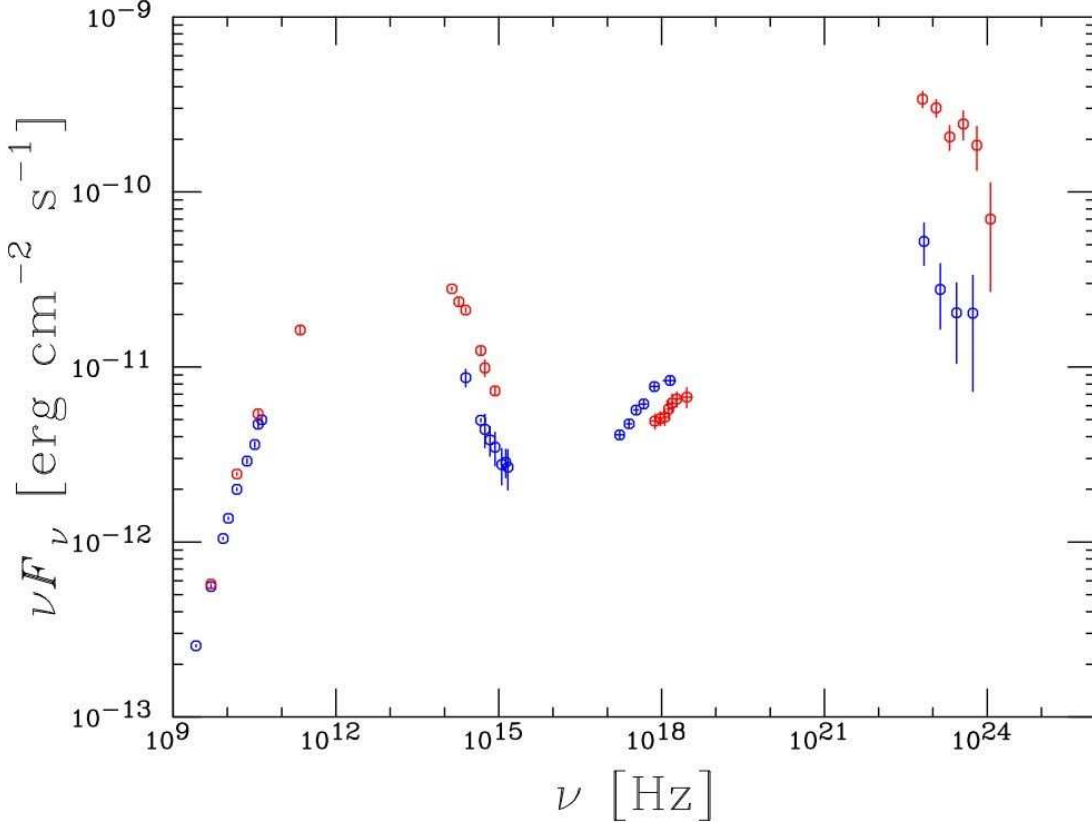
The gradual rotation of the optical polarization angle requires a non-axisymmetric trajectory of the emission pattern, since in a uniform, axially-symmetric case, any e.g., compression due to a shock moving along the



**Fig. 1.** Multi-frequency light curves of 3C 279 obtained during the large MW campaign between July 2008 and June 2009 (see Abdo et al. 2010b for details). Many MW facilities participated such as *Swift*-XRT and RXTE at X-ray bands; many telescopes of the GASP collaboration, Kanata, *Swift* UVOT and KVA at IR/optical/UV bands, as well as SMA, UMRAO, OVRO, Metsähovi, Medicina, Noto and Effelsberg at radio bands. Note the smooth optical polarization angle swing during the period of the second, rapid  $\gamma$ -ray flare (dotted lines).

jet would result in a change of polarization degree, but not in a gradual change of the EVPA. Consequently, two models have been discussed to explain the observed behavior in a non-axisymmetric/curved geometry: the emission region/knot propagating outwards along (i) helical magnetic field lines (similar to the optical polarization event observed in BL Lacertae, Marscher et al. 2008) and (ii) along the curved trajectory of a bent jet.

In both scenarios the distance of the dissipation region from the central engine can be constrained from the  $\sim 20$  day time-scale of the event. The distance obtained is about 5 orders of magnitude larger than the gravitational radius of the black hole in 3C 279 and implies a jet opening angle of  $< 0.2^\circ$ , smaller than typically observed with VLBI. Although less likely, models resulting in a much



**Fig. 2.** The red data points denote the period of the  $\gamma$ -ray/optical event. The blue data points have been taken during the period of the isolated X-ray flare (see Abdo et al. 2010b for details).

smaller distance (sub-parsec) can not be completely ruled out. At the large distances implied by the two models (parsec), the seed photons for the IC emission should then mostly be provided by the torus IR and jet synchrotron emission rather than BLR or accretion disk emission.

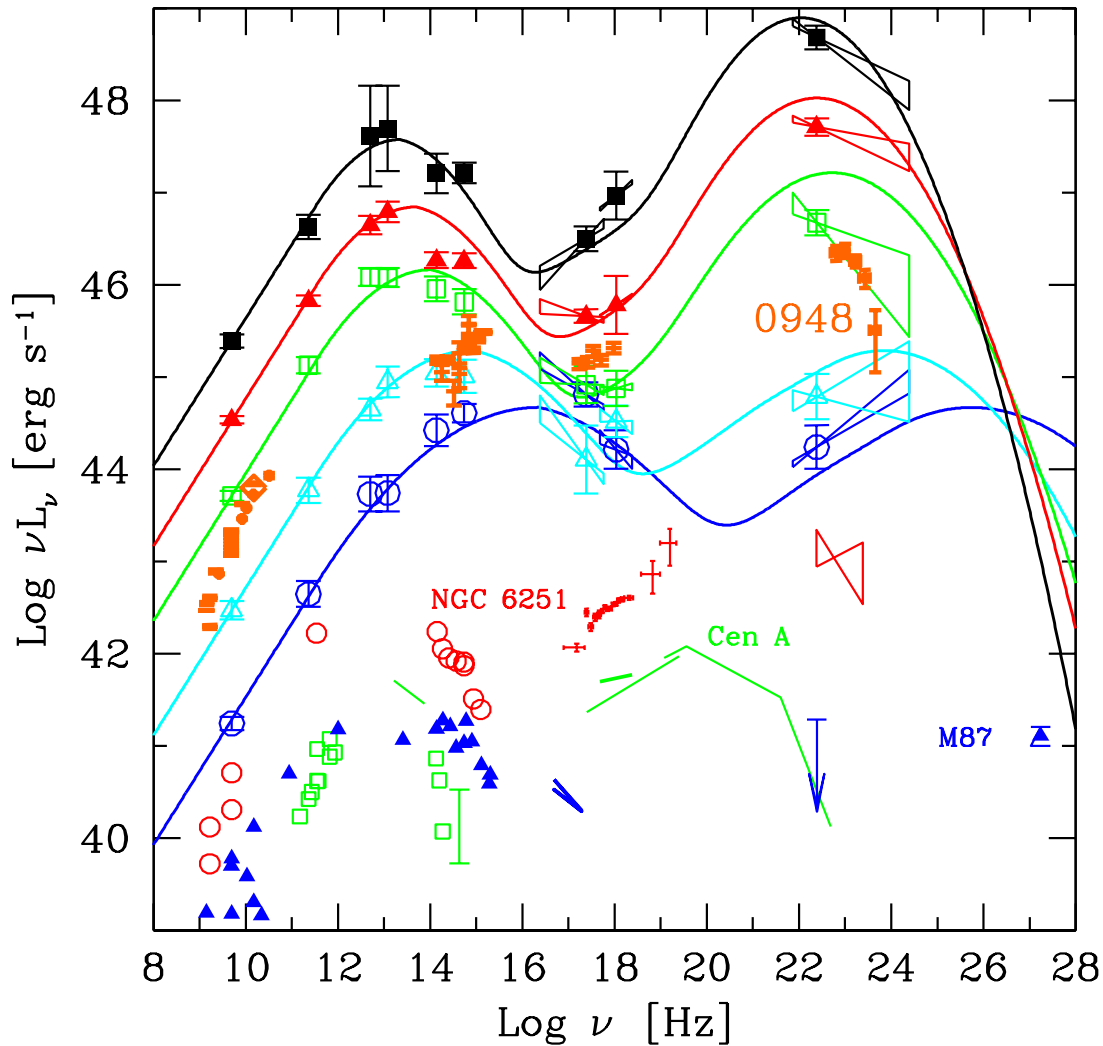
Another interesting feature is the isolated X-ray flare at MJD 54950, about 60 days after the second  $\gamma$ -ray flare. The hard X-ray spectrum during this period and the similarity of its shape and time-scale to the  $\gamma$ -ray flare argue in favor of an isolated event which is difficult to reconcile with simple one-zone models.

### 3. PMN J0948+0022 and Narrow-line Seyfert 1 galaxies

Before the launch of *Fermi*-GST the known types of  $\gamma$ -ray emitting AGN were blazars and radio galaxies. Indeed, the early *Fermi*/LAT three month results (Abdo et al. 2009c) confirmed that the extragalactic  $\gamma$ -ray sky is dominated by radio-loud AGN, being mostly blazars and a few radio galaxies. However, an important and impressive early discovery of *Fermi*-GST is the detection of  $\gamma$ -rays from a different class of AGN: Narrow Line Seyfert 1 galaxies (NLS1). These types of objects are believed to be active nuclei similar to those of Seyferts with optical spectra showing permitted lines from the broad-line region, although much narrower than typically seen in Seyfert 1s or blazars ( $\text{FWHM}(\text{H}\beta) < 2000 \text{ km s}^{-1}$ ). This and other characteristics make them a unique class of AGN, whereas a large fraction is radio-quiet, and only less than 7%

(Komossa et al. 2006) are found to be radio-loud. The first *Fermi*/LAT detection of  $\gamma$ -rays from a NLS1, namely in PMN J0948+0022 (Abdo et al. 2009b), certainly once more raised the question whether relativistic jets exist in this type of object, as indicated by previous studies in particular for the most radio-loud NLS1 (e.g., Foschini et al. 2009a).

The answer came promptly. MW follow-up observations of PMN J0948+0022 performed right after its  $\gamma$ -ray detection (Abdo et al. 2009b) as well as through a triggered MW campaign during March–July 2009 (Abdo et al. 2009d) demonstrated the efficiency of MW observations/campaigns in conjunction with *Fermi*/LAT: these MW studies have demonstrated that PMN J0948+0022 hosts a relativistic jet. Here, early SED studies using non-simultaneous plus simultaneously acquired MW data (Effelsberg 100-m, OVRO 40-m, *Swift* satellite) revealed an SED similar to that of powerful FSRQs with the typical double-humped appearance peaking in the far-IR and in the 40–400 MeV range (see Fig. 3). Signs of the accretion disk peaking in the *Swift* UV frequency range are clearly seen, which yields a lower limit to the black hole mass of  $1.5 \times 10^8 M_\odot$ . The time-resolved SEDs have been fitted using the one-zone synchrotron/IC model of Ghisellini & Tavecchio (2009) resulting in synchrotron/SSC components (dominating the radio to X-ray frequencies) and an EC component producing the  $\gamma$ -ray emission. The physical parameters are similar to those of blazars, however, with lower power compared to FSRQs but higher values than typically seen for BL Lacs (see Fig. 3).



**Fig. 3.** The SED of PMN J0948+0022 as obtained during the MW campaign, here shown in comparison to other  $\gamma$ -ray emitting FSRQs, BL Lacs and radio galaxies (from Foschini et al. 2009b, see also Abdo et al. 2009b, Abdo et al. 2009d).

From the radio perspective alone, the presence of a relativistic jet in PMN J0948+0022 appears obvious due to several findings, such as (i) flux density as well as spectral variability/flare over the duration of the campaign with flat ( $\alpha_{5-15\text{ GHz}} \sim 0$ ) to highly inverted (max.:  $\alpha_{5-15\text{ GHz}} = 0.98 \pm 0.05$ ) Effelsberg/RATAN radio spectra, (ii) equipartition Doppler factors of up to  $\sim 7$ , (iii) a highly compact, unresolved core on pc-scales (MOJAVE VLBA and EVN/LBA) with a 15 GHz core size of  $< 60 \mu\text{as}$  and corresponding core brightness temperature of  $1.0 \times 10^{12}\text{ K}$  and finally, (iv) VLBI core fractional linear polarization of 0.7%. This is the signature of a relativistic radio jet similar to those seen in powerful blazar type objects. The radio flare seen in the OVRO/Metsähovi light curves as well as Effelsberg/RATAN radio spectra appears to be delayed with respect to the  $\gamma$ -ray peak by 1.5–2 months.

In summary, the *Fermi*/LAT and MW observations of PMN J0948+0022 clearly demonstrate for the first time the existence of a  $\gamma$ -ray emitting NLS1 hosting a relativistic jet similar to blazars even though the environment in the vicinity of the central engine is most likely pretty different. However, this strongly challenges our view that jets can only develop in elliptical galaxies. Follow-up

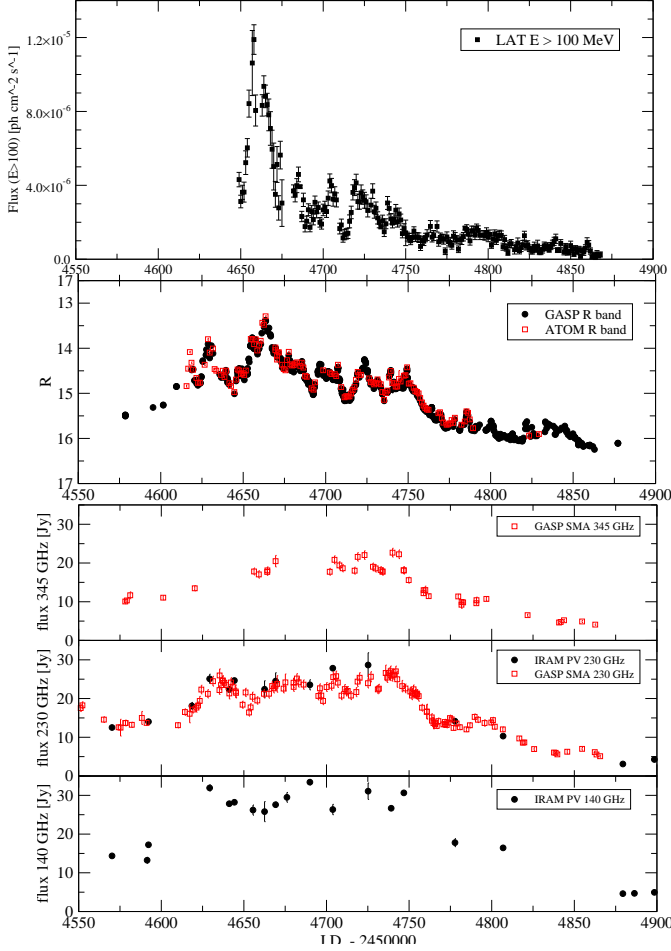
*Fermi*/LAT and MW observations of PMN J0948+0022 and the three other NLS1 detected by *Fermi*/LAT (Abdo et al. 2009e) will certainly shed further light on this interesting new type of  $\gamma$ -ray emitting AGN.

#### 4. The early $\gamma$ -ray flare of 3C 454.3 during 2008

During the early check-out phase of *Fermi*/LAT and the subsequent early operation in survey mode (July–October 2008), strong and highly variable  $\gamma$ -ray emission from the quasar 3C 454.3 was detected (Abdo et al. 2009a) showing a large outburst in July 2008 and subsequently, distinct symmetrically shaped sub-flares on time scales of days (see Fig. 4).

Such rapid  $\gamma$ -ray variability indicates a highly compact emission region and relativistic beaming with a Doppler factor of  $\delta > 8$  in order to be optically thin to pair production. The observed  $\gamma$ -ray spectrum obtained from the early *Fermi*/LAT data has demonstrated for the first time the existence of a spectral break for a high-luminosity blazar above 100 MeV, which may be regarded as evidence for an intrinsic break in the energy distribution of the radiating particles. Alternatively, the spectral softening above 2 GeV could be due to  $\gamma$ -ray absorption via photon-photon





**Fig. 4.** Selection of multi-band light curves for 3C 454.3 (Abdo et al. in prep.) obtained at  $\gamma$ -rays, optical R band (GASP and ATOM telescopes) and mm/sub-mm bands (SMA, IRAM 30-m). Note the similar variability pattern.

pair production on the soft X-ray photon field of the host active galactic nucleus or due to the superposition of two different spectral components at high energies (Abdo et al. 2009a, see also Finke & Dermer 2010 for a more detailed study of the spectral break).

The large multi-wavelength campaign (Abdo et al. in prep.) triggered by the *Fermi* AGN team shortly after the detection of the high  $\gamma$ -ray state of the source in July/August 2008, resulted in a so far unprecedented frequency coverage from cm/mm/sub-mm bands, IR/optical/UV, X-ray to the GeV range. These data sets demonstrate an active phase of 3C 454.3 across the whole electromagnetic spectrum. Figure 4 shows a selection of MW light curves including the  $\gamma$ -ray, optical (R) and short-mm bands. Interestingly, a similar variability pattern is seen at all bands, even down to the short-mm bands - up to frequencies higher than or close to the radio synchrotron turn-over at around 100 GHz. A detailed time series and cross-band analysis of the best sampled light curves reveals (i) strong correlations between  $\gamma$ -ray/optical and optical/mm-bands (ii) a quasi-periodic modulation of the variability with a fast (about 20 days)

and slow (about 60 days) component seen at all bands, with similar start and stop times. The optical polarization angle data, however, shows no obvious strong pattern, in contrast to the case of 3C 279.

Doppler factors in the range of 3–9 derived from the radio variability (Fig. 4) are in good agreement with those obtained from synchrotron self-absorption and  $\gamma$ -pair production arguments. Three epochs of multi-frequency VLBA ToO observations clearly show that the total single-dish variability originates from the core region while the core spectrum nicely resembles the (inverted) total single-dish spectrum.

The evolution of the synchrotron turnover frequency as obtained from the detailed radio light curves shown in Fig. 4 is in good agreement with the shock-in-jet model of Marscher & Gear (1985) (as are the increasing time lags towards longer radio wavelengths), at least in the synchrotron and adiabatic phases. However, departures from the Compton phase indicate additional processes at work as indicated already by the cross-band analysis. Detailed modeling with geometrical (e.g., helical jet) as well as SSC/EC models are in progress in order to explain the complex behavior of the source in a consistent manner.

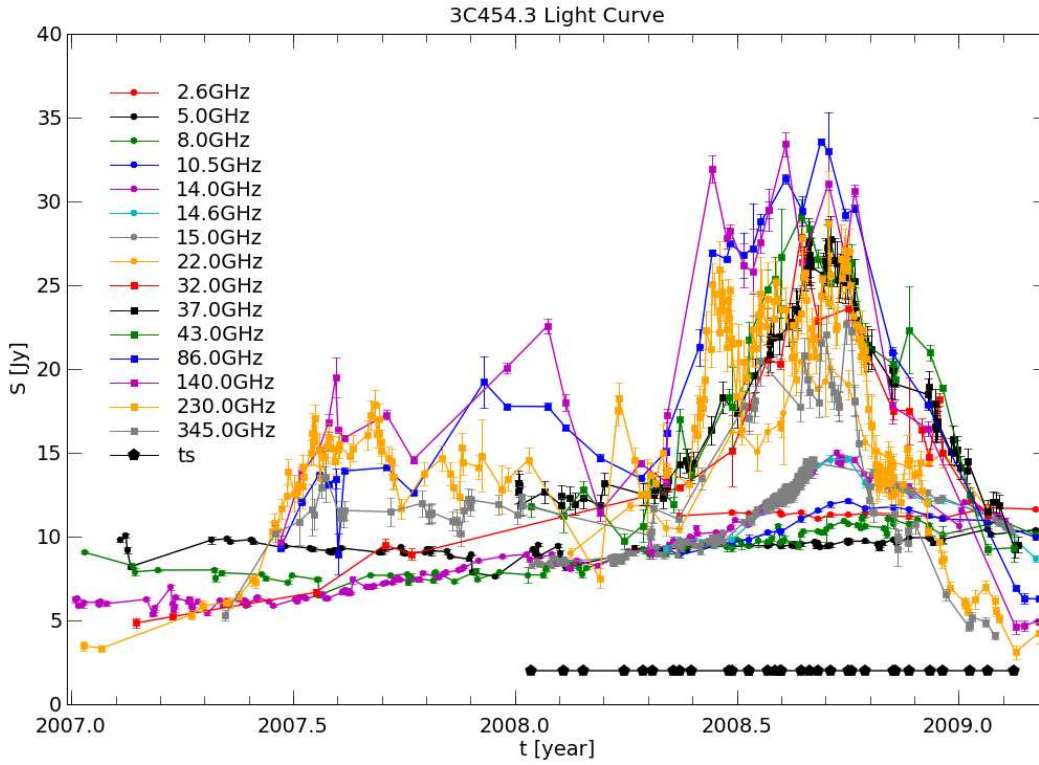
## 5. Conclusions

As a powerful “all-sky-monitor” the *Fermi*/LAT instrument provides a unique opportunity to explore the high energy  $\gamma$ -ray sky and the  $\gamma$ -ray characteristics of the AGN population. In particular, when combined with ground- and space-based multi-frequency observations, *Fermi*/LAT unfolds its full capability in addressing fundamental questions about energy production in AGN. This becomes possible due to the large efforts of the MW community in providing detailed, (quasi-) simultaneous broad-band data for a large number of *Fermi*-detected AGN. Since 2008 the *Fermi* team has triggered a large number of MW campaigns. The success of such campaigns, although challenging for both observers and theoreticians—as demonstrated by the examples presented here—increasingly provides deeper insight into the physical processes involved.

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**Fig. 5.** The full collection of multi-frequency radio cm/mm/sub-mm light curves of 3C 454.3 obtained during the MW campaign (Abdo et al. in prep.). Many radio telescopes were involved: UMRAO, Medicina, Noto, Effelsberg, OVRO, Metsähovi, IRAM 30-m, SMA. The great frequency coverage has been used to study detailed spectral evolution.

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